From Quantum Medium to Gravitational Sensor: A Triadic Framework for Unification via Energy, Information, and Movement

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Abstract

Reconciling quantum mechanics with general relativity remains the central unsolved problem of fundamental physics. This paper develops the *Medium–Sensor Framework* (MSF), a conceptual and explicitly hypothesis-level proposal that reframes the unification problem not as the merger of two incompatible mathematical formalisms but as the recognition of a functional complementarity between two operational layers of a single system. In this picture quantum mechanics describes the *Medium*—the fundamental, discrete, probabilistic substrate in which energy, information, and movement reside—while gravity is reinterpreted as an emergent *Sensor*: a coarse-grained, relational readout that translates the state of the Medium into the geometry of spacetime. The two layers are connected by a proposed scale-invariant dynamical loop built from the triad of Energy, Information, and Movement (E–I–M). We give an operator formulation of the loop based on the Heisenberg equation of motion, augmented by a dissipative term that we tie explicitly to the Gorini–Kossakowski–Sudarshan–Lindblad generator of open-system dynamics, and we present a candidate information-sourced field equation together with a full dimensional analysis and a discussion of covariant conservation. We situate the framework within the existing literature on emergent and entropic gravity, holography and the Ryu–Takayanagi formula, loop quantum gravity and spin-foam coarse-graining, and decoherence theory, showing that MSF functions as a unifying meta-language that brings these results into a single explanatory picture. We then present eight observational arenas—from gravitationally induced entanglement to gravitational-wave memory and the dark-energy equation of state—not as closed predictions but as collaborative testing grounds where the framework's central questions can be put to empirical inquiry, each mapped to an active or near-term experimental programme. A forward-looking section sets out the open questions the framework sharpens, foremost the construction of an action principle, and identifies these as a concrete research programme rather than obstacles. We offer MSF in a spirit of methodological humility: as a well-motivated, testable proposal whose value lies in organising disparate results around a single rule and in inviting the community to test it.

Keywords: quantum gravity; emergent gravity; holographic principle; decoherence; gravitationally induced entanglement; quantum information; unification

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1. Introduction

The two great theoretical achievements of twentieth-century physics describe the world in mutually incompatible languages. Quantum mechanics (QM), and its relativistic extension into quantum field theory, portrays reality as discrete, probabilistic, and non-local: physical quantities are operators on a Hilbert space, states evolve unitarily, and outcomes are governed by amplitudes whose squared moduli give probabilities. General relativity (GR), by contrast, portrays gravity as the smooth, deterministic curvature of a four-dimensional spacetime manifold, sourced by the energy and momentum of matter through Einstein's field equations. Each theory is extraordinarily successful within its domain. Yet every attempt to apply them jointly—to the interior of a black hole, to the first instants of the universe, or to the gravitational field of a particle in superposition—produces tension, ambiguity, or outright divergence. The search for a framework in which QM and GR coexist consistently has occupied theoretical physics for the better part of a century and remains its defining open problem.

The dominant research programmes have, for the most part, pursued a single strategy: *quantize gravity*. String theory embeds the graviton among the vibrational modes of fundamental extended objects and seeks a consistent ultraviolet completion of gravity within a larger, highly symmetric structure. Loop quantum gravity (LQG) applies canonical or path-integral quantization directly to the gravitational field, yielding a discrete quantum geometry of spin networks and spin foams. Other approaches—causal sets, causal dynamical triangulations, asymptotic safety, group field theory—differ in technique but share the premise that the metric, or whatever replaces it at short distance, is itself a quantum dynamical variable to be promoted to operator status.

This paper explores a different premise. We ask whether the persistent difficulty of quantizing gravity might be a signal that gravity is not, at the fundamental level, the kind of thing that should be quantized—that the metric is not a microscopic dynamical variable on the same footing as the electron field, but rather an emergent, collective, *coarse-grained* description of an underlying quantum substrate. On this view the incompatibility between QM and GR is not a contradiction to be resolved by forcing the two into a common formalism, but an expected feature of a layered reality in which the two theories describe different operational levels of one system. This intuition is not new. It is the common thread running through the thermodynamic derivation of the Einstein equation, through entropic and emergent-gravity proposals, and through the holographic reconstruction of bulk geometry from boundary entanglement. What we add is an attempt to name the layers and the rule that connects them, and to organise the existing results around that rule.

We call the quantum substrate the *Medium* and the emergent gravitational description the *Sensor*, and we propose that the two are linked by a scale-invariant dynamical cycle built from three primitives: Energy, Information, and Movement (the E–I–M loop). The Medium is the arena of quantum mechanics, where energy is quantized, information is encoded in states and their correlations, and movement is unitary evolution. The Sensor is gravity understood as a relational network that detects the distribution and flow of energy and information in the Medium and responds by organising those data into spacetime curvature. The collection of these ideas we call the Medium–Sensor Framework (MSF).

1.1. An inquiry framed as open questions

We present the MSF in a spirit of methodological humility, as a set of well-motivated open questions about the nature of reality rather than a system of settled claims. This stance is not a rhetorical concession; in foundational physics it is the posture most likely to invite the scrutiny and collaboration through which ideas mature. Three questions organise the framework, and the reader may find it useful to hold them in mind throughout.

The first is ontological: *what is the fundamental substrate of reality?* The framework's proposed answer is the Medium—the quantum substrate in which all particles, fields, and rules operate, characterised by discreteness, probability, non-locality, and constant dynamism (Section 2). The second arises from everyday experience: *how does smooth, continuous spacetime emerge from a fundamentally discrete quantum world?* The proposed answer is the Sensor—an emergent, coarse-grained response field that reads the state of the Medium and renders it as the geometry we perceive (Section 3). The third is the deepest: *what unifying rule governs the interaction between the microscopic quantum realm and the macroscopic gravitational one?* The proposed answer is the E–I–M loop, a scale-invariant cycle in which the apparent differences between quantum and gravitational phenomena reduce to the resolution at which the Sensor reads the Medium (Section 4).

Framed this way, the framework's strengths come into focus. It is, first, a genuinely *unifying* reading: the "functional complementarity" of QM and GR brings a striking number of otherwise disconnected results into one picture—Jacobson's thermodynamic derivation of the Einstein equation, Verlinde's entropic gravity, the Ryu–Takayanagi relation between entanglement and area, the spin-foam coarse-graining programme, and the decoherence account of the quantum-to-classical transition. Second, it is *concrete* enough to carry a definite mathematical anatomy—an open-system evolution for the Medium and an information-sourced effective geometry for the Sensor—whose structure we make explicit and subject to the standard consistency checks of dimensional analysis and covariant conservation. Third, and most importantly for a physical proposal, it is *testable*: framing the problem this way maps each major unresolved question onto an active or near-term experiment (Section 6), turning the abstract aspiration to unify QM and GR into a collaborative, evidence-based research programme.

We are equally clear about what remains to be done, and we treat these not as defects to be hidden but as the shared agenda of the programme. The framework does not yet derive from an action principle, and it does not yet issue a single quantitative prediction that is uniquely its own. We regard the construction of that action principle and the extraction of such a prediction as the central, well-defined tasks ahead, and we lay them out explicitly in Section 8. A reader looking for a finished quantum theory of gravity will not find one here; a reader looking for a coherent, testable way of *organising the search* may find the framework useful.

1.2. Relation to emergent-gravity programmes

The closest intellectual relatives of the MSF are the emergent- and entropic-gravity programmes. In 1995 Jacobson showed that Einstein's field equation can be derived as a local equation of state, by demanding that the Clausius relation $\delta Q = T\,\mathrm{d}S$ hold across every local Rindler horizon, with entropy proportional to horizon area [1]. This remarkable result implies that the field equation

of gravity may carry no more fundamental content than the laws of thermodynamics carry about the microscopic dynamics of a gas: it is a relation among coarse-grained quantities that holds regardless of the microscopic details. Padmanabhan extended this thermodynamic reading of gravity in a series of works [2], and Verlinde proposed that gravity might be understood as an entropic force arising from the tendency of an underlying system to maximise entropy [3]. On the holographic side, Van Raamsdonk argued that the connectivity of spacetime itself is built from the entanglement of the underlying degrees of freedom, so that disentangling a boundary state pulls the corresponding bulk geometry apart [4].

The MSF is best read as an attempt to give these programmes a common vocabulary. Where Jacobson speaks of an equation of state, the MSF speaks of the Sensor reading the Medium; where Van Raamsdonk speaks of geometry built from entanglement, the MSF speaks of information gradients sourcing curvature. We do not claim priority for any of the physical content—it belongs to the authors just cited and to the wider literature on holography and quantum information in gravity. We claim only that the Medium/Sensor/E–I–M language may be a useful way to see these results as facets of one picture, and that the picture in turn suggests where to look next.

1.3. Organisation

Section 2 develops the notion of the Medium as the quantum substrate. Section 3 develops the Sensor as an emergent, coarse-grained gravitational readout and situates it in the emergent-gravity literature. Section 4 formalises the E–I–M loop, giving the operator dynamics, the open-system extension, the candidate field equation, a dimensional analysis, and a discussion of conservation. Section 5 examines how the framework maps onto string theory, loop quantum gravity, and the holographic principle. Section 6 presents eight experimental arenas as collaborative testing grounds for the framework's questions. Section 7 applies the framework to the measurement problem, the black-hole information paradox, the arrow of time, and the cosmological-constant problem. Section 8 is a candid catalogue of the framework's limitations and the open problems that a complete theory would have to solve. Section 9 concludes.

2. The Medium: Quantum Mechanics as the Fundamental Substrate

The first pillar of the framework is the identification of the quantum domain as the fundamental layer of reality—the *Medium*. By "Medium" we mean the granular, discrete, probabilistic stage upon which all physical processes unfold. It is the arena of quantum mechanics, in which energy exists in quantized packets, information is encoded in quantum states, superpositions, and entanglement, and change is effected through unitary evolution. The Medium is not a substance in the classical sense; it is the totality of quantum degrees of freedom together with the rules that govern their correlation and evolution.

2.1. The three primitives

Within the Medium we distinguish three inseparable aspects, which together furnish the vocabulary of the E–I–M loop introduced in Section 4.

Information refers to the state, configuration, and correlations that define what exists. In

the language of quantum mechanics it is carried by the wavefunction ψ, or more generally by the density matrix ρ, and quantified by measures such as the von Neumann entropy $S(\rho) = -\operatorname{Tr}(\rho \ln \rho)$ and by entanglement entropies of subsystems. Information in this sense is not a passive label but the very content whose transformation constitutes physics.

Energy is the capacity for change. It is represented by the Hamiltonian operator $\hat{H}$, whose spectrum fixes the allowed stationary states and whose action drives the evolution of every other quantity. Without energy the information content of the Medium would be frozen; a vanishing Hamiltonian implies a static state.

Movement is the execution of transitions between states. At the level of the isolated Medium, movement is unitary time evolution, $|\psi(t)\rangle = U(t)|\psi(0)\rangle$ with $U(t) = \exp(-i\hat{H}t/\hbar)$; at the macroscopic level, as we shall argue, it appears as geodesic flow in a curved background. Movement is what carries energy and rewrites information, and it is the dynamical glue of the triad.

2.2. The mathematical home of the Medium

It is worth being precise about the mathematical structures that carry the three primitives, because the precision pays off when we formalise the loop. The Medium is described, in the standard way, by a separable Hilbert space $\mathcal{H}$, with pure states represented by rays $|\psi\rangle \in \mathcal{H}$ and general (mixed) states by density operators ρ: positive, self-adjoint, trace-one operators on $\mathcal{H}$. The Information primitive is carried by ρ itself and by the functionals built from it. The most important of these is the von Neumann entropy,

$$S(\rho) = -\operatorname{Tr}(\rho \ln \rho), \tag{1}$$

which vanishes for a pure state and is maximal for a maximally mixed one. When the Medium is partitioned into a subsystem A and its complement B, with reduced state $\rho_A = \operatorname{Tr}_B \rho$, the entanglement entropy $S(\rho_A)$ measures the quantum correlation between the parts. This quantity is the natural candidate for the "information density" whose gradients the Sensor is hypothesised to read, and it is the very quantity that appears on the left of the Ryu–Takayanagi relation (2). The identification is not accidental: it is the reason the holographic results of Section 3 are the framework's strongest anchor.

The Energy primitive is carried by the Hamiltonian $\hat{H}$, a self-adjoint operator whose spectral decomposition $\hat{H} = \sum_n E_n |n\rangle\langle n|$ fixes the stationary states and their energies. The Movement primitive is carried by the one-parameter unitary group it generates, $U(t) = e^{-i\hat{H}t/\hbar}$, which acts on states by $|\psi(t)\rangle = U(t)|\psi(0)\rangle$ and on observables, in the Heisenberg picture, by $\hat{A}(t) = U^\dagger(t)\,\hat{A}\,U(t)$. Differentiating the latter recovers equation (3), which is therefore not an additional assumption but the infinitesimal expression of unitary Movement. We labour this point because it is the one place where the E–I–M loop is exact and uncontroversial: the controversial content of the framework lies entirely in what happens when the Sensor coarse-grains this exact dynamics, not in the dynamics itself.

2.3. Discreteness, non-locality, and the failure of the classical picture

The Medium is characterised by precisely those features that have historically resisted geometrisation. Its observables are in general non-commuting, so that conjugate quantities cannot simultaneously possess sharp values; its correlations can be non-local, violating Bell inequalities and resisting any description in terms of local hidden variables; and its spectrum of allowed values is frequently discrete. These are not defects to be smoothed away but the defining signatures of the fundamental layer. The smooth, continuous, deterministic world of classical physics—and of the spacetime manifold of general relativity—is, on the MSF view, not the fundamental description but an emergent, coarse-grained one. The central claim of the next section is that the agent of that coarse-graining is gravity itself, acting as a Sensor.

3. The Sensor: Gravity as an Emergent, Coarse-Grained Readout

The second pillar reinterprets gravity. In the standard view gravity is a fundamental interaction, to be mediated at the quantum level by a spin-2 graviton and quantized like any other field. In the MSF view gravity is instead an emergent phenomenon: a *Sensor* whose function is not to compete with quantum mechanics but to read and respond to the state of the Medium, organising quantum events into a coherent macroscopic geometry. The observable signature of the Sensor is the curvature of spacetime, understood as the geometric readout of the Medium's informational and energetic state.

3.1. Coarse-graining and the weakness of gravity

The defining property of the Sensor is that it is *coarse-grained*. It operates at a lower resolution than the underlying quantum dynamics, integrating fine-grained fluctuations of the Medium over space and time. This integration averages out the delicate superpositions and probabilistic fuzziness of the Medium, leaving only the robust, stable patterns that we experience as the smooth deterministic world of classical physics. The analogy we find most apt is thermodynamic: just as temperature and pressure are not properties of individual molecules but emergent descriptions of their collective statistics, so spacetime curvature is, on this view, not a property of individual quantum events but an emergent description of their collective informational structure.

This perspective offers a natural reading of one of the oldest puzzles in physics: the extreme weakness of gravity relative to the other interactions. If gravity were a primary microscopic force it would be difficult to understand why its coupling is some forty orders of magnitude smaller than the electromagnetic coupling. If, however, gravity is a secondary, collective response to the coarse-grained behaviour of the Medium, then its apparent weakness is not a fine-tuning to be explained but a consequence of its derived status—the residual, large-scale imprint of a vast number of averaged microscopic events. We stress that this is a qualitative narrative, not a derivation of the value of Newton's constant; we return to its limitations in Section 8.

3.2. Intellectual lineage: thermodynamic and entropic gravity

The notion that the gravitational field equation is a coarse-grained, thermodynamic relation rather than a fundamental microscopic law has a precise and respected pedigree, and it is the

foundation on which the Sensor concept rests. Jacobson's 1995 derivation [1] obtains the full nonlinear Einstein equation from the Clausius relation $\delta Q = T\,\mathrm{d}S$ applied to local Rindler horizons, with the Unruh temperature supplying T and the area law supplying $\mathrm{d}S$. The logic is exactly that of the Sensor: geometry (the left-hand side of Einstein's equation) is fixed by the flow of energy and the change of entropy—that is, of information—across a horizon. Padmanabhan [2] developed an extensive thermodynamic interpretation of gravitational dynamics, showing that the field equations in a broad class of theories can be written as a balance of degrees of freedom on a holographic screen. Verlinde [3] proposed that gravity emerges as an entropic force, the macroscopic manifestation of a system's statistical tendency to increase its entropy.

In the holographic setting, the connection between information and geometry becomes quantitative. The Ryu–Takayanagi formula [5] states that the entanglement entropy S_A of a region A of the boundary theory equals the area of the minimal bulk surface γ_A anchored on ∂A, divided by $4G_N$:

$$S_A = \frac{\mathrm{Area}(\gamma_A)}{4G_N}. \tag{2}$$

Equation (2) is, in the language of the present framework, a direct statement of the Sensor's transfer function: it tells us precisely how much geometry (area) the Sensor produces in response to a given amount of quantum information (entanglement entropy) in the Medium. Van Raamsdonk's argument [4] that spacetime connectivity is sewn together by entanglement is the same statement read in reverse.

We do not present these results as confirmations of the MSF; they predate it and stand on their own. We present them to make clear that the Sensor concept is not an arbitrary metaphor but a re-description of an established and active line of research, and to fix the standard against which the framework's own, more speculative, contributions must be judged.

3.3. The Sensor and hidden dimensions

A subsidiary hypothesis, which we flag as considerably more speculative than the coarse-graining picture, is that the Sensor may operate across spatial dimensions hidden from the Medium's local interactions. If the gravitational readout propagates into extra dimensions while the Medium's gauge interactions are confined to the familiar three, the dilution of the gravitational response across the additional volume would furnish a second, geometric, contribution to gravity's weakness. Such a scenario predicts deviations from the Newtonian inverse-square law at sub-millimeter separations. We treat this not as a commitment of the framework but as one of several phenomenological avenues, and we discuss its stringent current experimental constraints in Section 6.

4. The Energy–Information–Movement Loop: Formalisation

To advance beyond a conceptual narrative the framework must be given a mathematical anatomy. We do not claim to derive that anatomy from first principles; we claim only to specify it precisely enough that its requirements, consistency conditions, and points of failure become explicit. This section presents the operator dynamics of the loop, its extension to open-system evolution, and a candidate information-sourced field equation, each accompanied by the consistency checks a referee would demand.

4.1. Operator dynamics of the loop

Let $\hat{I}$ denote an Information operator—for concreteness, an observable whose expectation tracks a chosen informational property of the Medium—let $\hat{H}$ be the Hamiltonian (the Energy operator), and let the time derivative $\partial/\partial t$ represent Movement. For an isolated Medium the evolution of $\hat{I}$ in the Heisenberg picture is governed exactly by the Heisenberg equation of motion,

$$\frac{\mathrm{d}\hat{I}}{\mathrm{d}t} = \frac{i}{\hbar}\,[\hat{H}, \hat{I}]. \tag{3}$$

Equation (3) is not a new postulate; it is a cornerstone of quantum mechanics, and we adopt it unchanged. Its role in the framework is interpretive: it states that Movement (the rate of change of Information) is *generated* by Energy (the action of $\hat{H}$) on Information ($\hat{I}$). The commutator $[\hat{H}, \hat{I}] = \hat{H}\hat{I} - \hat{I}\hat{H}$ quantifies how the Hamiltonian reshuffles the distinctions encoded in the information observable. A vanishing Hamiltonian gives $\mathrm{d}\hat{I}/\mathrm{d}t = 0$: no energy, no movement, frozen information. A large commutator gives rapid informational flow. This is the E–I–M loop in its cleanest form, and it is exact.

4.2. From closed to open: the dissipative term and its GKSL form

Equation (3) describes the *isolated* Medium, evolving unitarily and reversibly. The Sensor, however, is by construction a coarse-grained observer: it integrates over degrees of freedom and thereby discards information to inaccessible scales. The effective dynamics of the Medium as seen through the Sensor must therefore be *open*, including irreversible processes such as decoherence. We write this as

$$\frac{\mathrm{d}\hat{I}}{\mathrm{d}t} = \frac{i}{\hbar}\,[\hat{H}, \hat{I}] + \mathcal{D}(\hat{I}, \hat{H}), \tag{4}$$

where $\mathcal{D}$ is a dissipator encoding the coarse-graining. It is essential not to leave $\mathcal{D}$ undefined. The theory of open quantum systems fixes its admissible form: if the reduced dynamics is to remain completely positive and trace-preserving and to form a quantum dynamical semigroup, then by the Gorini–Kossakowski–Sudarshan–Lindblad (GKSL) theorem [6, 7] the generator must take the form, here written in the Schrödinger picture for the density matrix ρ,

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\frac{i}{\hbar}[\hat{H}, \rho] + \sum_k \gamma_k \left(L_k \rho L_k^\dagger - \tfrac{1}{2}\{L_k^\dagger L_k, \rho\} \right), \tag{5}$$

with jump operators L_k and non-negative rates $\gamma_k \geq 0$. The dissipator $\mathcal{D}$ in (4) is then the Heisenberg-picture adjoint of the second term of (5). Identifying the coarse-graining of the Sensor with a concrete set of jump operators—most naturally, operators that monitor the Medium in the pointer basis selected by the system–environment coupling, in the sense of Zurek's einselection [8]—is the route by which the schematic $\mathcal{D}$ would be made rigorous. We do not carry out that identification here for a realistic Hamiltonian; we note only that the framework *requires* $\mathcal{D}$ to be of GKSL type, and that this requirement is a nontrivial, falsifiable structural constraint rather than a free choice.

4.3. A candidate information-sourced field equation

The Sensor's defining task is to translate the Medium's state into geometry. We encode this with a candidate generalisation of the Einstein field equation in which curvature is sourced not only by the usual stress–energy but by gradients of an information field. Writing $G_{\mu\nu}$ for the Einstein tensor, we propose

$$G_{\mu\nu} = \kappa \left(\nabla_\mu \nabla_\nu \mathcal{I} \; + \; \langle T_{\mu\nu}(\hat{H}) \rangle_{\text{coarse}} \right), \tag{6}$$

where $\mathcal{I}$ is a scalar information field (a coarse-grained c-number descendant of $\hat{I}$), $\langle T_{\mu\nu}(\hat{H}) \rangle_{\text{coarse}}$ is the coarse-grained expectation of the stress–energy tensor built from the Hamiltonian, and κ is a coupling constant. The first term expresses the hypothesis that pronounced gradients in information density—regions of strong, structured quantum correlation in the Medium—are read by the Sensor as curvature; the second recovers the familiar matter source in the appropriate limit.

We are obliged to be explicit that equation (6) is written by analogy and is *not* derived from an action principle. It must therefore be checked against, and in its present form does not automatically satisfy, the consistency conditions that any admissible field equation must meet. We turn to these now.

4.4. Dimensional analysis

A field equation that fails dimensional consistency is not even a candidate. We work in geometrised-natural conventions and restore factors where they clarify. The Einstein tensor has dimensions of inverse length squared, $[G_{\mu\nu}] = L^{-2}$. In standard GR, $G_{\mu\nu} = 8\pi G\, c^{-4}\, T_{\mu\nu}$, with $[T_{\mu\nu}] = \text{energy density} = M\, L^{-1}\, T^{-2}$ and $[8\pi G\, c^{-4}] = L\, M^{-1}\, T^2 \cdot L^{-2} \cdot \ldots$ combining to give L^{-2} as required.

Consider now the information term $\kappa\, \nabla_\mu \nabla_\nu \mathcal{I}$. The double covariant derivative carries dimensions $[\nabla\nabla] = L^{-2}$ acting on whatever dimension $\mathcal{I}$ possesses. For the product to match $[G_{\mu\nu}] = L^{-2}$ we require

$$[\kappa] \cdot L^{-2} \cdot [\mathcal{I}] = L^{-2} \quad \Longrightarrow \quad [\kappa]\,[\mathcal{I}] = 1 \text{ (dimensionless)}. \tag{7}$$

If $\mathcal{I}$ is taken to be a dimensionless information measure (as von Neumann entropy in natural units is, being defined through $-\operatorname{Tr}\rho \ln \rho$), then κ must likewise be dimensionless in these units—which is problematic, because the second term of (6) requires κ to carry the dimensions of $8\pi G/c^4$ in order to reproduce GR. *The two terms on the right-hand side of* (6) *therefore cannot share a single coupling κ unless $\mathcal{I}$ is assigned compensating dimensions of an energy density*, i.e. $[\mathcal{I}] = M\, L^{-1}\, T^{-2}$ scaled by an appropriate power of length so that $\nabla\nabla\mathcal{I}$ matches $T_{\mu\nu}$. This is a genuine defect of (6) as written. The minimal honest repair is to introduce two distinct couplings,

$$G_{\mu\nu} = \kappa_{\mathcal{I}}\, \nabla_\mu \nabla_\nu \mathcal{I} \; + \; \kappa_T\, \langle T_{\mu\nu}(\hat{H}) \rangle_{\text{coarse}}, \qquad \kappa_T = \frac{8\pi G}{c^4}, \tag{8}$$

with $[\kappa_{\mathcal{I}}] = L^2/[\mathcal{I}]$ fixed by whatever dimension is chosen for the information field. We adopt (8) in preference to (6) for the remainder of the paper, and we flag the determination of $\kappa_{\mathcal{I}}$ from a microscopic model as an open problem.

4.5. Covariant conservation and the Bianchi constraint

The contracted Bianchi identity guarantees $\nabla^\mu G_{\mu\nu} = 0$ identically. Any admissible field equation must therefore have a right-hand side that is also covariantly conserved. For (8) this demands

$$\kappa_{\mathcal{I}}\, \nabla^\mu \nabla_\mu \nabla_\nu \mathcal{I} \;+\; \kappa_T\, \nabla^\mu \langle T_{\mu\nu} \rangle_{\text{coarse}} = 0. \tag{9}$$

In ordinary GR the matter sector satisfies $\nabla^\mu T_{\mu\nu} = 0$ on its own. If that continues to hold for the coarse-grained stress–energy, then (9) reduces to the nontrivial requirement

$$\nabla^\mu \nabla_\mu \nabla_\nu \mathcal{I} = 0, \tag{10}$$

i.e. the information field must be such that the divergence of its Hessian vanishes. This is a strong constraint: it is *not* satisfied by a generic scalar field, and it tells us that $\mathcal{I}$ cannot be freely specified but must obey its own field equation consistent with (9). Equivalently, the information and matter sectors must exchange "energy" in a precisely compensating way if each is not separately conserved. We regard the derivation of the $\mathcal{I}$ field equation—ideally as the Euler–Lagrange equation of a shared action $S[g_{\mu\nu}, \mathcal{I}, \psi]$ whose metric variation yields (8)—as the single most important piece of unfinished business for the framework, and we say so again, emphatically, in Section 8.

4.6. A worked example of the conservation constraint

To make the constraint of Section 4.4 and the present subsection concrete, consider the linearised, weak-field regime, in which $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ with $|h_{\mu\nu}| \ll 1$. To first order the Einstein tensor reduces to a linear differential operator on $h_{\mu\nu}$, and covariant derivatives become ordinary partial derivatives. The conservation condition (9) then reads, schematically,

$$\kappa_{\mathcal{I}}\, \Box\, \partial_\nu \mathcal{I} + \kappa_T\, \partial^\mu \langle T_{\mu\nu} \rangle_{\text{coarse}} = 0, \tag{11}$$

where $\Box = \partial^\mu \partial_\mu$ is the flat d'Alembertian. If the coarse-grained matter is independently conserved, the information field must satisfy $\Box\, \partial_\nu \mathcal{I} = 0$, which is solved by any $\mathcal{I}$ whose gradient is harmonic. This is restrictive but not empty: it admits, for example, information fields that are linear in the coordinates or that satisfy a massless wave equation. The lesson is that the framework does not permit $\mathcal{I}$ to be chosen arbitrarily once (8) is imposed; the geometry-information coupling and the conservation law together pin down a dynamics for $\mathcal{I}$ that a complete theory would have to derive from an action. We regard this worked example as the clearest available statement of what "deriving the $\mathcal{I}$ field equation" would concretely require.

4.7. An explicit decoherence model for the dissipator

The claim that $\mathcal{D}$ must be of GKSL form is most convincing when illustrated by a standard model. Consider a single quantum degree of freedom monitored by an environment in the position basis—the canonical model of decoherence. The reduced dynamics takes the Lindblad form (5)

with a single jump operator proportional to the position operator, $L = \sqrt{\Lambda}\,\hat{x}$, giving

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\frac{i}{\hbar}[\hat{H}, \rho] - \Lambda\,[\hat{x}, [\hat{x}, \rho]], \tag{12}$$

where Λ is a decoherence rate fixed by the system–environment coupling. In the position representation the second term multiplies the off-diagonal elements $\rho(x, x')$ by $-\Lambda(x - x')^2$, so coherences between distinct positions decay on a timescale that shrinks rapidly with their separation. This is precisely the mechanism—einselection in the position (pointer) basis [8]—by which the Sensor's coarse-graining would suppress macroscopic superpositions and yield the classical limit. Within the MSF, Λ acquires an interpretation as a measure of the rate at which the Sensor reads, and therefore disturbs, the Medium. We do not claim a derivation of Λ from gravitational physics; we claim only that (12) shows the schematic $\mathcal{D}$ of (4) can be instantiated by a legitimate, completely-positive generator, and that doing so connects the framework to the established and experimentally tested theory of decoherence.

4.8. A pedagogical simulation

To illustrate that the loop is at least internally coherent as a dynamical system, one can implement a deliberately simplified numerical toy model. A `QuantumMedium` object holds a state vector ψ on a one-dimensional lattice and evolves it by $\psi(t + \mathrm{d}t) = \exp(-i\hat{H}\,\mathrm{d}t/\hbar)\,\psi(t)$ (the Movement step driven by Energy). At each step one computes the probability distribution $|\psi|^2$ as a proxy for local information content and the local energy expectation as a proxy for $\langle T_{\mu\nu}\rangle$. A `GravitySensor` object then maps these to a curvature field via a discretised version of (8)—schematically, a Laplacian of the information field plus the energy density—and updates an effective metric. Iterating closes the loop. We emphasise that such a simulation is *pedagogical only*: it demonstrates that "information evolves, energy drives the evolution, geometry responds" can be turned into running code, but it proves nothing about nature, since the curvature map is imposed by hand rather than derived. Its sole purpose is to make the proposed causal structure tangible.

5. Alignment with Major Programmes in Quantum Gravity

A recurring theme of this paper is that the MSF is best understood not as a competitor to existing quantum-gravity programmes but as an interpretive meta-language in which their shared architecture becomes visible. We now make that claim concrete for the three most developed programmes: string theory, loop quantum gravity, and the holographic principle. In each case we identify which structures play the role of the Medium, which play the role of the Sensor, and what realises the E–I–M translation rule. We are careful to mark where the correspondence is genuinely illuminating and where it is merely suggestive.

5.1. String theory

In string theory the fundamental objects are vibrating one-dimensional strings and higher-dimensional branes, whose vibrational modes correspond to the spectrum of particles and forces. In MSF language these objects and their excitations are the carriers of Energy; the precise state

of a string—its topology, winding numbers, and boundary conditions—encodes Information; and the dynamics of string interaction, together with the web of dualities (T-duality, S-duality) relating apparently distinct string theories, constitute Movement: pathways connecting configurations of the Medium without altering its physical content. The higher-dimensional bulk in which the strings propagate plays the role of the Sensor, with familiar four-dimensional spacetime emerging as an effective slice.

The deepest point of contact is the gauge–gravity duality. We discuss it in its own right below, but note here that the much-debated "landscape" of string vacua and the field's gradual shift of emphasis from fundamental strings toward emergence and duality sit comfortably within the framework: from the MSF standpoint the specific microscopic constituents are secondary to the functional roles they play, so the move toward treating geometry as emergent is precisely what the framework expects. We do not pretend this resolves any technical problem of string theory; it is an interpretive alignment, offered as such.

5.2. Loop quantum gravity

The correspondence with loop quantum gravity is more direct, because LQG already builds a discrete quantum substrate and already faces the problem of recovering smooth spacetime by coarse-graining. The quantum states of geometry in LQG are spin networks—graphs whose edges carry spin labels and whose vertices carry quanta of volume [9]. In the MSF reading the spin network *is* the Medium: the discrete substrate whose labels (spins, holonomies) are the Information, encoding quanta of area and parallel transport. The Hamiltonian constraint operator supplies the Energy that generates dynamics. The evolution of a spin network—the spin foam, a sum over histories of networks—is the Movement of the loop [10].

The crucial point of convergence is coarse-graining. LQG must recover the smooth spacetime of GR as a large-scale limit of the discrete spin-network structure, and this is achieved through coarse-graining and renormalisation procedures that average over small-scale quantum-geometric detail [11, 12]. This is, by definition, the function of the Sensor. The renormalisation-group goal of restoring diffeomorphism symmetry at large scales translates, in MSF language, into the requirement that the Sensor's response become invariant under coordinate transformations—the hallmark of classical GR. We regard LQG as the programme that most concretely realises the Medium and the coarse-graining Sensor, and we draw on its rigorous notion of coarse-graining rather than using the word loosely.

5.3. The holographic principle and AdS/CFT

The strongest alignment is with the holographic principle, whose sharpest realisation is the AdS/CFT correspondence [13]. The principle—anticipated by 't Hooft [14] and Susskind [15], and rooted in the Bekenstein bound [16]—holds that the description of a region of space can be encoded on its boundary. In the AdS/CFT dictionary, the boundary conformal field theory is a quantum theory without gravity: it is the quintessential Medium, containing all the degrees of freedom of the system. The bulk gravitational theory in anti-de Sitter space is the Sensor, reconstructing a higher-dimensional geometry from boundary data. The dictionary mapping boundary operators to bulk fields is an explicit, if incompletely known, realisation of the E–I–M

translation rule.

Two results make the correspondence quantitative. The Ryu–Takayanagi formula (2) [5] relates boundary entanglement entropy to bulk minimal-surface area, fixing the Sensor's transfer function as discussed in Section 3. The ER=EPR conjecture [17] posits that entangled pairs are connected by Einstein–Rosen bridges, so that entanglement (Information in the Medium) is the very stuff of spacetime connectivity (the Sensor's geometric response). These are, in our reading, the clearest existing demonstrations that information in the Medium generates geometry in the Sensor. The subsequent islands/quantum-extremal-surface programme and its reproduction of the Page curve [18, 19, 20, 21] extend the relation into the dynamical, evaporating-black-hole regime, and we discuss its bearing on the information paradox in Section 7.

5.4. Distinction from neighbouring proposals

Because the framework borrows heavily from emergent-gravity ideas, it is fair to ask what, if anything, distinguishes it from its neighbours. We answer directly. From pure entropic gravity [3] the MSF differs in retaining a definite microscopic substrate (the Medium) with unitary quantum dynamics, rather than positing an entropic force as primitive; the dissipation enters only through the Sensor's coarse-graining, not through the Medium itself. From analogue-gravity programmes it differs in claiming that the coarse-graining relation is not merely analogical but is the actual mechanism of gravitation, a far stronger and correspondingly more vulnerable claim. From approaches that identify quantum gravity outright with quantum information theory it differs in assigning distinct functional roles—content-bearing Medium versus structure-forming Sensor—rather than collapsing the two. And from timeless or block-universe formulations it differs in treating temporal directionality as emergent from the irreversible integration of the loop, as set out in Section 7. We do not present these distinctions as advantages; some readers will regard the additional commitments as liabilities. We present them so that the framework's location in the space of proposals is unambiguous, and so that it can be attacked or defended on its actual content.

5.5. Synthesis

Read together, the three programmes furnish complementary realisations of one architecture: LQG provides the most explicit construction of a discrete quantum Medium and of the coarse-graining that defines the Sensor; string theory provides rich examples of the Sensor's behaviour in higher dimensions and the duality web that realises Movement; and holography provides the overarching principle—and, in RT and ER=EPR, the quantitative rules—by which the Medium's information is translated into the Sensor's geometry. The MSF suggests that the ultimate theory may be characterised less by a single master equation than by a single *rule*—Energy plus Information plus Movement—expressed through two complementary roles. We advance this as a unifying narrative and a research heuristic, not as a theorem.

6. Experimental Arenas for Collaborative Inquiry

A framework earns scientific standing through its contact with experiment, and here the MSF is unusually fortunate: the questions it raises map directly onto a suite of active and near-

term experimental programmes. Rather than presenting the following eight arenas as closed predictions issued from the armchair, we present them as *testing grounds*—the collaborative junctures at which the framework's central questions can be put to empirical inquiry. For each we state what the framework leads us to expect, what a given outcome would demonstrate, and which experimental community is best placed to carry the test forward. This is, in effect, a roadmap for a multi-decade, evidence-based research programme, and an invitation to the experimentalists who are already building the relevant apparatus.

6.1. Gravitationally induced entanglement (the BMV experiment)

The most immediate and exciting arena is the Bose–Marletto–Vedral (BMV) proposal [22, 23]. Two masses, each placed in a spatial superposition, are allowed to interact only gravitationally; if they emerge entangled, then under broad and well-studied assumptions the gravitational interaction cannot be a local classical channel, since local operations and classical communication cannot create entanglement. This is a direct probe of the Sensor's central function: a Sensor that reads and conveys the quantum information of the Medium should be able to mediate exactly such correlations, and the MSF therefore anticipates a positive result. With first results anticipated in the 2026–2028 window, this is a genuine near-term opportunity, and the pioneering groups behind the proposal—notably those associated with Marletto and Vedral—furnish the natural collaborators for testing the Sensor's role.

We read the surrounding theoretical activity as encouraging rather than threatening. A positive BMV result would establish that gravity is non-classical in a precise sense; the question of exactly *what* it then implies about the mediator is live and fruitful, and the MSF sits comfortably within that conversation. We return in Section 8 to a particularly resonant recent contribution—the demonstration that a locally classical mediator can generate entanglement [24]—which aligns strikingly with the framework's picture of a Sensor that conveys quantum effects while itself remaining a coarse-grained, locally classical readout.

6.2. Engineered geometry in quantum simulators

Cold-atom and other quantum simulators allow engineered patterns of entanglement to be prepared in the laboratory and the resulting collective, effective-geometric response to be read out, for instance by mapping the quantum Fisher information to an emergent metric signature. These platforms are a remarkable gift to the framework: they realise, at laboratory scale and under exquisite control, precisely the Medium-to-Sensor translation the E–I–M loop describes—information structure organising an effective geometry. Proof-of-concept demonstrations already exist, and the programme of scaling them toward gravitationally relevant regimes offers a hands-on testbed for the principle of emergent geometry. While a tabletop analogue does not by itself settle how gravity behaves cosmically, it provides the cleanest available demonstration that the framework's core mechanism is physically realisable.

6.3. Lorentz-invariance tests with gamma-ray bursts

If the Sensor's coarse-grained readout carries discrete structure near the Planck scale, high-energy photons might propagate at very slightly energy-dependent speeds, producing arrival-time

differences across the spectrum of a gamma-ray burst. Fermi-LAT observations have already reached extraordinary sensitivity: the energy scale of any linear-in-energy vacuum dispersion must exceed of order a few $\times 10^{17}$ GeV, with the single-burst bound from GRB 090510 exceeding the Planck energy for the linear case [27, 28], and the Cherenkov Telescope Array will extend the reach further. We note that the framework does not *require* Lorentz violation—coarse-graining can perfectly well preserve Lorentz symmetry—so this arena functions as an open question: a detection would point toward a discrete Sensor, while the continuing null results comfortably accommodate a Lorentz-preserving coarse-graining, which is itself a clean and testable position.

6.4. Short-range tests of the inverse-square law

The optional extra-dimensional reading of the Sensor (Section 3) raises the question of whether gravity deviates from the Newtonian $1/r^2$ law at short range. The Eöt-Wash torsion-balance experiments have answered with beautiful precision, confirming Newtonian behaviour down to $52\,\mu$m and bounding gravitational-strength Yukawa interactions to ranges below $38.6\,\mu$m [29, 30]. This sharpens, rather than closes, the question: it tells any extra-dimensional variant exactly which parameter space remains open, and it leaves the framework's core—which does not depend on extra dimensions—entirely intact. Atom-interferometric platforms such as MAGIS-100 and AION will probe complementary regimes in the coming years.

6.5. Gravitational-wave memory

The framework leads us to expect that the most extreme events in the universe should leave lasting imprints on the Sensor. The gravitational-wave memory effect—a permanent strain offset associated with Bondi–Metzner–Sachs supertranslations—is exactly such an imprint, and its anticipated detection with next-generation detectors such as Cosmic Explorer and the Einstein Telescope (and, in the population, with current detectors) is a milestone the framework welcomes [31]. Memory is a firm prediction of classical general relativity, so its observation will be a triumph for the established theory; the open and inviting question the MSF adds is whether high-precision ringdown and memory measurements might eventually reveal subtle quantum imprints of the Medium, a question that next-generation sensitivity will be the first to address seriously.

6.6. The dark-energy equation of state

One of the framework's most suggestive readings is of cosmic acceleration as the Sensor's baseline response to the growing information content of an expanding Medium—that is, as a *dynamical* rather than static phenomenon. It is therefore striking that recent results from the Dark Energy Spectroscopic Instrument, combined with cosmic-microwave-background and supernova data, show a preference for an evolving dark-energy equation of state over a bare cosmological constant [32]. This is precisely the qualitative direction the framework points, and the open and well-defined task it sets is to derive a specific functional form $w(z)$ that the next generation of surveys—Euclid, the Rubin Observatory's LSST, and the Roman Space Telescope—can confront with data. We regard this as one of the most promising avenues for turning the framework's picture into a sharp cosmological test.

6.7. The quantum-to-classical transition

Optomechanical and matter-wave experiments that probe decoherence rates and measurement back-action test the coarse-graining picture at the very heart of the Sensor. Here the framework rests on especially firm ground, because it adopts the established and experimentally well-supported mechanism of einselection [8] as the route to the classical limit. The arena thus serves as a foundational consistency check that the framework passes by construction, and a deepening of these experiments toward ever-larger masses continues to probe the boundary the Sensor is hypothesised to draw.

6.8. Variation of fundamental constants

The most exploratory of the eight questions asks whether the "constants" of nature might reflect optimal Sensor translation parameters and so correlate with large-scale information structure, a possibility testable through high-resolution spectroscopy with the ELT and JWST. Current bounds on such variation are already tight, which makes this a demanding test; we flag it as the framework's most open-ended phenomenological frontier and an invitation for future theoretical sharpening.

6.9. A roadmap for collaborative testing

Taken together, these eight arenas turn the framework into a programme rather than a position. The table below collects them as a roadmap: for each guiding question we note the framework's expectation, the experimental community already engaged, and an indicative timeline. The honest and energising summary is that the MSF is compatible with everything we currently observe and stands to be sharpened—and genuinely tested—by experiments that are being built right now. The task the framework sets itself, and offers to the community, is to convert each consistency into a quantitative, discriminating prediction; the mathematical route to doing so is the subject of Section 8.

Guiding question	**Framework expectation**	**Experimental arena**	**Timeline**
QM–GR unification	Gravity mediates entanglement (Sensor reads the Medium)	BMV interferometry	2026–2028
Spacetime emergence	Engineered entanglement reconstructs curvature	Cold-atom simulators	2025–2027
Gravity's weakness	Possible cross-dimensional dilution	MAGIS-100, AION; Eöt-Wash	2027–2030
Quantum-to-classical	Coarse-graining via einselection	Optomechanical systems	Ongoing
Arrow of time	Irreversible E–I–M integration	Cold-atom thermodynamics	2025–2028
Cosmic acceleration	Dynamical, information-sourced dark energy	Euclid, LSST, Roman	2026–2032
Black-hole information	Horizons as translation layers	LIGO/Virgo/KAGRA, CE, ET	2025–2030

Guiding question	**Framework expectation**	**Experimental arena**	**Timeline**
Physical constants	Correlation with information structure	ELT, JWST spectroscopy	2028–2035

7. Application to Foundational Problems

Beyond phenomenology, the value of an interpretive framework is tested by whether it casts foundational puzzles in a clarifying light. We consider four. In each case we present the MSF reading and then mark carefully the difference between a genuine resolution and a redescription.

7.1. The measurement problem

The MSF reading is that there is no physical collapse of the wavefunction. The Medium always evolves unitarily; the appearance of a definite classical outcome arises from the Sensor's coarse-graining, which integrates over fine-grained detail and resolves only the robust, einselected pointer states [8]. On this view, "measurement" enjoys no special status: any interaction that integrates information over sufficient scale—a detector, a rock, the cosmic microwave background—participates in the Sensor's coarse-graining. This is an attractive, naturalistic stance that places the quantum-to-classical transition on a continuum rather than treating it as a mysterious exception. We note, in the spirit of open inquiry, that it shares with decoherence theory generally one residual question: decoherence explains the suppression of interference and the selection of a basis, while the passage from an improper mixture to a single experienced outcome remains a matter of interpretation. The framework's contribution is to give that open question a natural home in the structure of the Sensor. **Contribution: a naturalistic, continuum account of the classical limit; the residual interpretive question is shared with all decoherence-based approaches.**

7.2. The black-hole information paradox

The framework recasts the event horizon not as a locus of information destruction but as a high-density translation layer between Medium and Sensor: information crossing the horizon is encoded into the Sensor's geometric degrees of freedom rather than lost, preserving unitarity. This picture resonates with several concrete results—the soft-hair proposal of Hawking, Perry and Strominger [33], in which horizon symmetries store information; and, far more decisively, the islands/quantum-extremal-surface programme, which reproduces the Page curve of an evaporating black hole and thereby shows how the entanglement entropy of Hawking radiation can fall back to zero as unitarity demands [18, 20, 21]. We are clear that the technical work of resolving the paradox has been done by that programme, not by the MSF; the framework offers a vocabulary consistent with it ("horizon as translation layer") but no independent calculation. We also note the alternatives the framework must contend with, including the firewall argument [34], which exposes the tension between unitarity, locality, and the equivalence principle that any resolution must address. **Contribution: a vocabulary that fits naturally with the islands**

resolution; the detailed calculation belongs to that programme, and connecting the two precisely is an inviting line of future work.

7.3. The arrow of time

The MSF proposes that time's directionality emerges from the irreversible integration of the E–I–M loop by the Sensor: as the coarse-grained record of state updates accumulates, the growth of accessible coarse-grained states realises the second law, and the low-entropy early universe is read as the initial condition of the Medium before large-scale integration began. This is a coherent statement of the thermodynamic origin of the arrow, consonant with the broader programme that grounds temporal asymmetry in coarse-graining and special initial conditions. The one question it leaves open—why the initial state of the Medium was so special—is the deepest form of the puzzle and is open to every account of temporal asymmetry, not to this one alone. **Contribution: a coherent thermodynamic origin for time's direction, locating the remaining puzzle in the initial condition of the Medium.**

7.4. The cosmological-constant problem

The framework suggests that cosmic acceleration is the Sensor's baseline response to the vacuum information density of the Medium, rather than a bare vacuum energy, potentially softening the notorious discrepancy between the quantum-field-theoretic estimate of the vacuum energy and the observed value. Here we must be especially careful with a frequently mis-stated figure. The often-quoted "120 orders of magnitude" is the *naive* estimate obtained from a Planck-scale momentum cutoff; more careful Lorentz-invariant regularisation arguments yield a substantially smaller—though still severe—mismatch [35, 36]. The MSF does not, at present, compute the residual value; it offers a direction (dynamical, information-sourced dark energy) rather than a solution. The recent evidence for evolving dark energy [32] makes that direction worth pursuing, and the framework's qualitative reading—dynamical, information-sourced dark energy—points squarely in the direction the data are now favouring. **Contribution: a promising direction consonant with the latest cosmological evidence; deriving the residual value is a well-defined task ahead.**

8. Open Questions and the Road Ahead

A healthy framework is one that knows exactly what work remains, and states it as a concrete agenda rather than a list of apologies. We have flagged open questions throughout; we gather them here as the framework's research programme—a set of well-defined tasks, each of which would move the MSF from a unifying perspective toward a fully predictive theory. We regard the existence of so clear an agenda as itself a strength.

1. Constructing the action principle. The most important and well-defined task ahead is to derive the framework's two dynamical statements—the open-system evolution (4) and the field equation (8)—from a single action $S[g_{\mu\nu}, \mathcal{I}, \psi]$. Such an action would secure general covariance, supply the matter couplings systematically, provide a Noether structure, and control quantum corrections. Building it, and confirming that it reproduces Einstein gravity and standard quan-

tum mechanics in the appropriate limits, is the step that would turn the framework into a theory in the full sense, and the structure laid out in Section 4 is designed to make that construction approachable.

2. Completing the field equation. Section 4.4 already does part of this work, replacing the dimensionally inconsistent single-coupling form by the two-coupling equation (8). What remains is to fix the coupling $\kappa_{\mathcal{I}}$ from a microscopic model and to derive the field equation for $\mathcal{I}$ implied by the covariant-conservation constraint (9)—a concrete and self-contained calculation.

3. Instantiating the dissipator. We have shown that the dissipator $\mathcal{D}$ in (4) must take GKSL form (5) and illustrated it with a standard position-basis decoherence model (12). Exhibiting the jump operators L_k for a realistic gravitational coupling, and tying the rate to a physical coarse-graining scale, is a well-posed next step that connects the framework directly to the mature theory of open quantum systems.

4. Sharpening a discriminating prediction. The framework is currently compatible with all relevant observations (Section 6); the task is to convert one of those consistencies into a quantitative prediction—a specific $w(z)$, a definite deviation in gravitational-wave memory, a calculable decoherence rate—that a named experiment can test. This is the operational counterpart of task 1, and the experimental arenas are already in place to receive it.

5. From meta-language to computation. The mappings of Section 5 are interpretive, and valuable as such: they bring disparate programmes into one picture. The open question is whether the E–I–M translation rule can be made computational—whether, for instance, the framework can add calculational content to the holographic dictionary rather than re-describing it. We regard this as a genuinely exciting long-term possibility.

A resonant complementary result. The framework's central picture—a Sensor that conveys the quantum effects of the Medium while itself remaining a coarse-grained, locally classical readout—finds a striking echo in very recent work. Tibau Vidal, Marletto, Vedral and Chiribella [24] demonstrate that a locally classical mediator can generate genuine entanglement between two quantum systems through what they term non-locally tomographic couplings, without requiring spacetime itself to be in superposition. Read through the lens of the MSF, their quantum matter sector corresponds to the Medium, their locally classical mediator to the Sensor, and their non-local coupling to the coarse-graining performed by the E–I–M loop. We do not present this as proof of the framework—it is an independent line of inquiry with its own assumptions, and the broader debate on what gravity-mediated entanglement implies remains vigorous and unsettled. But it offers a complementary mathematical pathway toward the very quantum–classical interface the framework describes, and clarifying the precise relationship between non-local tomography and the Sensor's coarse-graining is a natural and inviting direction for future work.

The programme in one sentence. Two achievements would elevate the MSF from a unifying perspective to a candidate theory: an action principle delivering (4) and (8) with consistent

dimensions and correct limits, and a single quantitative prediction a named experiment could confirm or refute. Both are well-defined, both are approachable, and both are offered here as an invitation to the community.

9. Conclusions

We have presented the Medium–Sensor Framework as a conceptual, explicitly hypothesis-level approach to the unification of quantum mechanics and general relativity. Its organising idea is that the two theories are not rivals but complementary operational layers of a single system: quantum mechanics describes the Medium, the fundamental substrate of energy, information, and movement; gravity is the Sensor, an emergent and coarse-grained readout that translates the Medium's state into spacetime geometry; and the two are linked by the scale-invariant Energy–Information–Movement loop. We gave the loop an operator formulation, extended it honestly to open-system dynamics of GKSL type, proposed a candidate information-sourced field equation, and—rather than presenting that equation uncritically—subjected it to dimensional analysis and to the covariant-conservation constraint, repairing it where it failed and flagging what remains underived.

We situated the framework within the emergent- and entropic-gravity programmes from which its core intuition derives, and we mapped it onto string theory, loop quantum gravity, and holography, showing that it functions as a unifying meta-language that draws these programmes into a single picture. We then presented eight observational arenas as collaborative testing grounds, each tied to an active or near-term experiment, and we set out the framework's open questions as a concrete, approachable research programme rather than a catalogue of obstacles.

What, then, is the framework for? Its value, we have argued, is at once unifying, concrete, and testable. It offers a single vocabulary in which Jacobson's equation of state, Verlinde's entropic force, the Ryu–Takayanagi relation, spin-foam coarse-graining, and einselection appear as facets of one picture. It carries a definite mathematical anatomy whose requirements we have made explicit and whose consistency we have checked. And it converts the broad aspiration to "unify QM and GR" into a programme with named experiments and well-defined next steps. The quest for a final theory may be less a search for the one true equation than for the one true rule—Energy, Information, and Movement, expressed through the complementary roles of Medium and Sensor. We offer the Medium–Sensor Framework in that spirit: as a well-motivated, testable, and openly stated proposal, and as an invitation to the theoretical and experimental communities to take up the questions it sharpens and to put them to the test.

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